CAAP Quarterly Report

Date of Report: *November 30th, 2020*

Prepared for: *U.S. DOT Pipeline and Hazardous Materials Safety Administration*

Contract Number: *693JK31850007CAAP*

Project Title: *AI-enabled ILI robot with integrated structured light NDE for distribution pipelines*

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For quarterly period ending: *November 30, 2020*

Business and Activity Section

(a) Contract Activity

Project abstract: Underground gas pipeline networks extend over 3 million miles in the United States of America. The aging of these infrastructures, combined with external damages from third-party excavation operations, is creating safety concerns for both operators and residents in the vicinity of these pipelines. In this proposal, we will collaborate with GTI/OTD and industry to develop an integrated AI-enabled robotic platform with a structured light-based NDE inspection tool for the scanning of medium density polyethylene (MDPE) pipes used in natural gas distribution. Unlike the direct optical inspection methods with cameras and light sources, the proposed tool will provide the operator with precise 3D information about the status of the pipe internal surface, which increases the probability of detection and leads to better damage evaluation capabilities. The tool will also provide an embedded electronic stabilization procedure to reduce the effect of vibration during the scanning process. The structured light sensor is mounted on a highly flexible sake robot that can carry the sensor and maneuver it through the complex gas pipelines networks. The AI-enabled shared control method combines autonomous decision support and high-level human commands to improve safety and usability of robot control.

In this project, our multi-university team will build on our prior work sponsored by PHMSA, OTD and DOE to enhance the capabilities of the scanning platform and improve the ease of operation, and foster the collaboration between academic institution (MSU, CSM), research institution (GTI) and industry (OTD, utility companies). This will be achieved by addressing the lessons learned during the initial testing in OTD roadmap project and the feedback from our industry partners. The main research objectives can be summarized as follows:

- Design and develop a structured light endoscopic sensor for the inspection of the pipe internal defects.
- Automate the scanning process to reduce the amount of expertise needed to perform the inspection and reconstruction process.
- Design and develop a flexible robotic platform to maneuver the sensor through the complex pipelines networks
- Implement a shared control method based on reinforcement learning to allow a user to control the robot more easily and safely.

Educational Objectives: Another major objective of the proposed effort is to inspire, educate and train Ph.D. and MS students to address pipeline safety challenges, potentially as a career after their graduation. If funded, three Ph.D. students from the three collaborating laboratories and several MS/undergraduate students will participate in this CAAP program. They will be trained and educated in science and engineering to address the pipeline safety and integrity challenges. The PIs believe that education is a critical component of the CAAP project, and we will integrate research with educational activities to prepare the next-generation scientists and engineers for the gas and pipeline industry. Specific educational objectives include:

- Inspiring, educating and training the graduate students at MSU and CSM as research assistants for pipe integrity assessment and management. Our previous successful CAAP projects have produced several engineers, researchers and summer interns in gas and pipeline industry,
- Integrating research topics from this effort with the existing undergraduate research programs at MSU, e.g. ENSURE program at MSU College of Engineering, and CSM, e.g., Mines Undergraduate Research Fellowship (MURF), to involve undergraduate students in pipe safety research.
- Improving the curriculum at MSU (e.g., Nondestructive Evaluation) and CSM (e.g., Artificial Intelligence and Human-Centered Robotics) using the scientific findings and achievement from the proposed research,
- Adapt research topics from this project to student projects in a seminar, senior design, and project courses, in order to make educational impacts on broader groups of students,
- Encourage the graduate research assistants involved in this project and students in the courses to apply for internships with USDOT/PHMSA and industry to practice their learned skills and gain practical experiences in areas related to pipeline safety and integrity.

The above-mentioned goals and objectives of this CAAP project will be well addressed and supported by the proposed research tasks. Development, demonstrations, and potential standardization to ensure the integrity of pipeline facilities will be carried out with the collaborative effort among two universities and our industry partner, Gas Technology Institution. The quality of the research results will be overseen by the PIs and the DOT program manager and submitted to high-profile and peer-reviewed journals and leading conferences. The proposed collaborative work provides an excellent environment for the integration of research and education as well as tremendous opportunities for two universities supported by this DOT CAAP funding mechanism. The graduate students supported by this CAAP research will be heavily exposed to ILI, NDE, reliability and engineering design topics for emerging pipeline R&D technologies. The PIs have been actively encouraging students to participate in past and ongoing DOT projects and present papers at national and international conferences. Students who are not directly participating in the CAAP project will also benefit from the research findings through the undergraduate and graduate courses taught by the PIs and through attending university-wide research symposium and workshop.

(b) Status Update of Past Quarter Activities

Below is a high-level summary of the activities performed during this quarter:

- The project kickoff meeting was held via teleconference and was attended by four teams from DOT, GTI, CSM (HRCL), MSU (SML), MSU (NDEL).
- The project will be extended to be 3 years instead of 2 years to account for any unexpected delays and guarantee the completion of all the proposed tasks.
- MSU(NDEL) updated the design of the SL sensor and initial work toward sensor synchronization was completed for Task 2.

- CSM (HRCL) made progress toward the educational objectives by incorporating materials from this project toward developing undergraduate courses and research at CSM.

(c) Cost share activity

No cost share activity to be reported in the first quarter.

(d) Task 0. Kickoff meeting:

The project kickoff meeting was held via teleconference and was attended by four teams from DOT, GTI, CSM (HRCL), MSU (SML), MSU (NDEL).

- DOT was represented by Zhongquan Zhou and Zaid Obeidi.
- GTI was represented by Ernest Lever and Khalid Farrag.
- MSU (NDEL) team was headed by Dr. Yiming Deng
- MSU (SML) team was headed by Dr. Xiaobo Tan.
- CSM (HRCL) team was headed by Dr. Hao Zhang.

A brief presentation was given by MSU and CSM teams to discuss the project objectives, methodologies, tasks structure, timeline, and deliverables. MSU (SML) will be responsible for the development of the robotic platform. MSU (NDEL) will be responsible for the development of the structured light 3D vision sensor. CSM (HRCL) will be responsible for the development of an intelligent shared-control algorithm to automate the maneuvering of the robot inside the pipe. The project will be extended to be 3 years instead of 2 years to account for any unexpected delays and guarantee the completion of all the proposed tasks.

Teams discussed the project objectives and the final expected deliveries. The teams also discussed the project execution plan and collaborations among different teams. In addition, the following issues were discussed during the meeting:

- The possibility of improving system battery life
- The possibility of using the gas flow inside the pipe for energy harvesting
- The advantages of using a tethered or an untethered robotic solution
- The need for surface preparations before the pipe inspection
- The effect of different surface colors on the sensor performance
- The effect of the pressurized gas environment on the system performance
- The possibility of adding some capabilities to the system to examine the inspection data and repeat the scans automatically

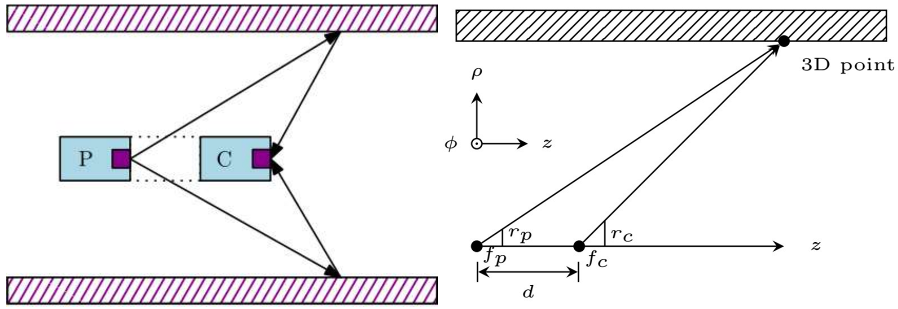
(e) Task 2: Redesign and optimization of the structured light sensor (NDEL at MSU)

In this task, MSU focuses on the development and optimization of an endoscopic structured light sensor. The design and development process will focus on addressing the shortcomings that we discovered in our initial trials of the integration of the robotic platform. A schematic of the proposed scanning platform is shown in **Figure 1.a**. The setup consists of a structured light projection module and a camera that is placed in front of the projector. In the proposed design, the camera and the projector are assumed to share the same main axis. By using symmetry around the main axis, the 3D triangulation can be reduced to 2D and the distance in the radial and axial directions can be calculated for each angle θ.

Figure 1.b shows the triangulation process in the system based on a pinhole camera model for both the projector and the camera. By assuming an equal focal length for the projector and the camera, the cylindrical coordinates of the point are given by:

$$z = \frac{d}{1 - \frac{r_p}{r_c}}, and\ \rho = \frac{r_p z}{f}$$

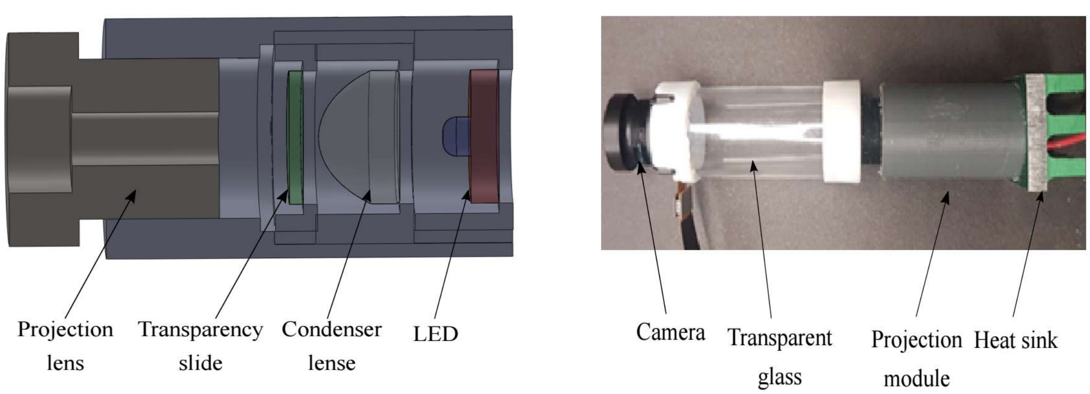
f_c is the camera focal length, f_p is the projector focal length, d is the distance between the camera and projector image planes. r_c is the position of the point in the camera image coordinates, and r_p is the position of the point in the projector image coordinates.



(a) (b)

Figure 1: a) Schematic of the structured light system in cylindrical geometry, b) Triangulation process in cylindrical geometry.

The pattern is designed to be a sequence of color-changing stripes. Color coding is preferred over intensity coding because it increases the number of available codes and enhances robustness against noise. The design of the slide projector consists of a high-intensity lamp, a collimation lens, a transparency slide, and a projection lens. The high-intensity lamp is the main light source that illuminates the transparency pattern. The light rays from the lamp are directed forward by a concave mirror and then the diverging rays are gathered and focused on the slide via the collimator lens. The slide is used to filter or block specific parts of the projected light according to the texture printed on the slide. Finally, a projection lens is used to direct and focus the image of the pattern on the projection plane. For the endoscopic sensor, the high-intensity lamp is replaced with a single high-intensity light-emitting diode with a light temperature of 5000 Kelvin to have a neutral light color. The light is then passed to a 10mm diameter aspheric condenser lens that collimates the diverging light beam from the LED onto the transparency slide. The slide is directly printed with an inkjet printer on transparency film. The projection of the light is performed by using a 3.6mm lens with an F2.0 aperture that is designed for a 0.5-inch sensor size. A schematic of the designed projector showing the main holder and the internal components is found in **Figure 2.a**. The holder's internal surface is engraved to have four rails to enable the insertion of the components sequentially. Each of the components is enclosed by a holder with four fins that are inserted into the main holder rails. The projector body and the lens holders are fabricated by using 3D printing to enable rapid prototyping for the projector. A wide-angle lens is used to increase the field of view (FOV) of the camera sensor to cover larger area of the pipe wall.



(a) (b)

Figure 2: a) Schematic of the light projection module. b) Picture of a fabricated SL sensor

A picture of the sensor explaining its main components is shown in Figure 2**.b**. A transparent glass tube is used to connect the camera and the projector to enable the projection of the colored rings to the pipe walls. One of the objectives of this project is to increase the rigidity of the sensor and improve its performance. The schematic of the upgraded SL sensor is shown in **Figure 3**. An array of white LEDs will be added to the front tip of the sensor, so that that the sensor can provide direct 2D images of the pipe in addition to the 3D map. The holders of the projector and the camera components will be machined out of aluminum. Hardened glass will also be added in front of the camera to provide protection to the camera lens. This new schematic will add more rigidity to the sensor body and add new capabilities to the sensor with the implementation of the synchronized sensor acquisition.

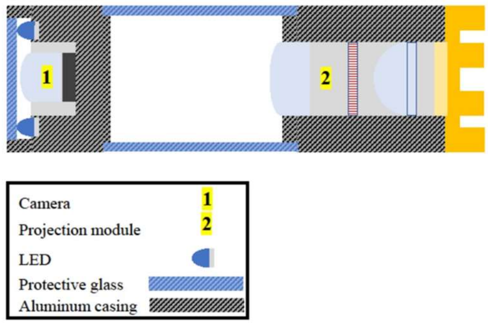


Figure 3: Schematic of the upgraded SL sensor

1. Motion effect reduction on the 3D reconstruction:

Mounting the sensor on a fast-moving platform can result in distortion of the final 3D profile and degradation of the overall system performance. The degradation is caused by the forward motion and the vibration of the platform. The effect of these types of motions can result in the following:

- Motion blur: this type of distortion results in blurred images during the acquisition phase, which leads to a reduction of system resolution. This effect can be mitigated by increasing the acquisition speed of the system; however, increasing the acquisition speed with the same light intensity leads to darker and noisier images. Therefore, the light source of the projection module will be upgraded to enable the use of higher shutter speeds.
- Rolling shutter effect: the imaging sensor reads the camera pixels sequentially (row by row); therefore, the fast movement will result in skewed images and deformed 3D reconstruction. This effect will be eliminated by implementing camera-flash synchronization (This will also lead to better heat management in the projection module).

To address these problems, we implement a synchronization algorithm that ensures tight synchronization between the camera and the projector. This approach is inspired by the techniques that MSU implemented during the development of 693JK31850007CAAP project where we performed LED-camera-projector synchronization with stereo cameras. Another factor to reduce the blur will be to increase the power of the light source to ensure fast acquisition time. In this quarter we focused on the development of the synchronization algorithm while the light source upgrade will be performed when the new sensor will be fabricated in the next quarter.

2. Sensor synchronization:

The camera sensor is built as an array of photodetectors that are aligned in the shape of the rectangular or square matrix. Each photodetector can be simulated as a bucket that is opened at the beginning of the exposure time to be filled with photons. The number of gathered photons over a specific period of time (exposure time) reflects the light intensity sensed by the camera for that specific photodetector (pixel). CMOS sensors can be classified by the method of pixels reading mechanism into two types, rolling shutter, and global shutter sensors. In a rolling shutter sensor, the camera cannot read all the pixels at the same time and the sensor matrix is read sequentially (row by row).

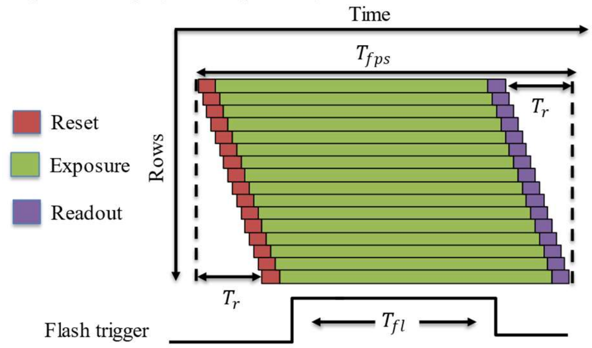


Figure 4: Synchronization with rolling shutter

Therefore, each row starts its exposure at a different time to ensure that all the pixels have the same amount of exposure time. I.e. even with fast shutter speed (short exposure times) the speed of the acquisition is slowed by the readout speed of the sensor. The effect of this type of sensor reading method can be recognized as a spatial distortion when imaging fast-moving objects. Another downside is that different regions of the image will have slightly different illumination in the case of using a fast-changing illumination source.

Global shutter sensors on the other side can have the ability to perform complete sensor readout at the same time. But this comes with a higher cost, more complexity, slower maximum framerate, higher readout noise, and lower dynamic range. To overcome this problem, DSLR cameras use mechanical shutters. In a mechanical shutter, an opaque curtain is placed in front of the sensor to block any incoming light from reaching the camera sensor while the shutter is closed. The curtain is opened at the beginning of the exposure time and then closed at the end of the exposure time. With the existence of a mechanical shutter, all the photocells start exposing at the same time when the curtain is opened, and the exposure ends when the curtain is closed even though the pixel was not read yet. Therefore, high shutter speeds can be achieved even with slow reading sensors. Mechanical shutters are a precise and robust solution for still photography with DSLR cameras but they are not reliable for continuous video acquisition and high frame rate. An alternative solution for dark environments is to modify the existing rolling shutter sensors to have global shutter like capability with careful light source synchronization.

Pipe internal atmosphere represents a dark environment with no access to ambient light because the pipes are buried underground. Therefore, the only light source in this environment is originated from the artificial illumination from the sensor head. This environment simplifies the design of the sensor because it eliminates the distortion from ambient light to the structured light pattern and provides tight control of the imaged scene illumination. In this case, we don't need to block the incoming light toward the senor, instead, a light source is required to provide illumination. Therefore, the dark environment will act as a natural shutter for the camera sensor. The frame exposure starts with a dark environment then a strong flash is illuminated in the middle of the frame exposure for a short time followed by sensor readout (the pulse period must be smaller than the exposure to guarantee even illumination across the frame). The implementation of this solution provides the following advantages:

- Allow synchronized acquisition by alternating between the projector and white LED
- Better power and thermal efficiency due to the smaller working time for the projector
- Reduce camera blur due to the faster shutter speeds where flash power is excited in a short period
- Solve rolling shutter problem and eliminate spatial distortion

The embedded acquisition platform provides the ability to direct the CSI control signals to one of the external general-purpose input-output (GPIO) pins. The signal is raised when the end of the first line in the frame is received from the sensor and falls when receiving the end of the last line in the frame. The exposure time starts after time T from receiving the last line of the image., i.e the signal falling edge serves as an indicator of starting a new frame. The delay can be calculated as follows:

$$T = \frac{1}{fps} - T_{ex}$$

The camera sensor is started with all the initial parameters regarding the exposure time, frames per second, and digital and analog gain. An external function is created to monitor camera signals and trigger the projector excitation.

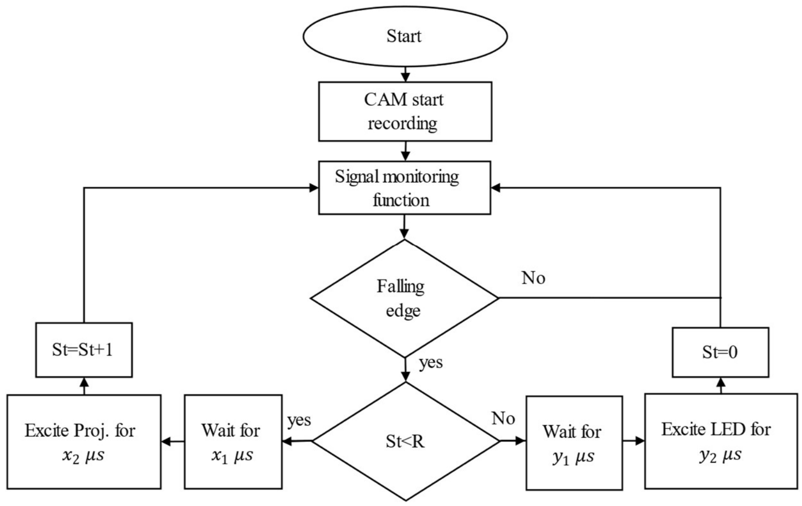


Figure 5: Synchronization algorithm.

Figure 5 shows a flow diagram of the recording and triggering algorithm. **Figure 6** shows the timing diagram of the camera acquisition signal and the projector excitation signal produced by the acquisition platform. Different pulsed widths are used to have precise control over the sensor exposure.

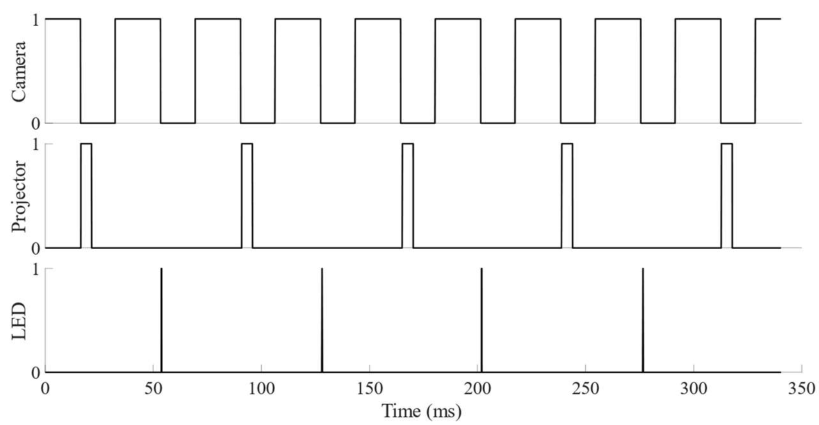


Figure 6: Synchronization timing diagram.

3. Discussion and future work:

During the past quarter, MSU worked to finalize the development plan for upgrading the SL sensor. A new schematic of the sensor was developed. The new design will provide more rigidity to the sensor body and add new inspection capabilities by incorporating camera-LED-projector synchronization. The new design will enable the sensor to acquire concurrent data acquisition of 3D and 2D data by alternating between the SL projector and white LED array. Initial work to implement the synchronization procedure was performed. The synchronization procedure will eliminate the effect of rolling shutter and reduce the camera blur. The future work will focus on fabricating the new sensor design, testing the synchronization algorithm, and continuing the work on the other proposed subtasks.

(f) Task 3. Intelligent shared-control for improved robot-assisted pipe inspection (HRCL at

Mines)

Colorado School of Mines made progress toward the educational objectives and that includes:

- Involving two graduate students in algorithm development at Mines.
- Introducing the application of robot-assisted pipeline inspection and the classic reinforcement learning methods in the course materials for CSCI 473/573 Human-Centered Robotics at Mines.
- Adapting the research topics from this project with existing Mines' undergraduate research programs.